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FOUR-CELL ROCKETBORNE MAGNETOMETER

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Final Report

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Research Directorate
AIR FORCE SPECIAL WEAPONS CENTER
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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(Prepared under Contract AF 29(601)-5120
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Air Force Systems Command
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ABSTRACT

The theory, design, installation, and successful operation of a four-gas-cell, wide-range, nearly omnidirectional rubidium-vapor magnetometer system intended for rocketborne use are described. Included is a detailed description of two coil systems and their power supplies and housing, comprising a magnetic test facility designed, fabricated, and installed at the Special Weapons Center.

Each magnetometer will operate continuously in ambient magnetic fields ranging in intensity from approximately 100 gammas to more than 1 oersted (10^5 gammas). Since Rb^{85} is employed in the gas cells, the Larmor frequency can vary from nearly zero to approximately 500 kc/s in this field range; a signal processor developed for this magnetometer "maps" any signal within this band into an output signal varying in frequency between a few hundred cycles per second and 100 kc/s.

PUBLICATION REVIEW

This report has been reviewed and is approved.

for Perry F. Heric Col USAF
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ILLUSTRATIONS

I. INTRODUCTION

This report outlines the design of a magnetometer system developed for continuous, omnidirectional, rocketborne measurement of the earth's total magnetic field intensity, including very rapid intensity fluctuations.

An extension of and improvement upon work done under a previous contract[1], each self-oscillating rubidium-vapor magnetometer system consists of a four-gas-cell sensing head, two lamps and their remotely located rf power oscillators, signal amplifiers and limiters, a signal processing unit, and a power regulator and converter. Each element is described in detail.

A complete magnetic test facility was built and installed at the Special Weapons Center; its construction and operation are described.

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[1] Contract No. AF 29(601)-2599. See Report No. AFSWC-TDR-62-25, "Rocket-Borne Magnetometer, Final Report," March, 1962. (Unclassified).

II. MAGNETOMETER SPECIFICATION

Each instrument delivered under this contract meets the following specifications:

1. Continuous self-oscillation at a rate of approximately 4.67 cycles per second per gamma (1 gamma = 10^{-5} oersted) as determined by the use of Rb^{85} in all gas cells is achieved over a frequency range of more than 500 kc/s. This corresponds to a field range of 100 gammas to over 100,000 gammas.

2. As discussed at length in previous reports[2], each instrument can respond to extremely rapid temporal variations in the measured field which occur over the stated range of field intensity. Such variations may be in the order of 10^9 gammas/second in intervals less than a millisecond.

3. Signals from each of the two dual-gas-cell oscillators comprising the magnetometer are combined into a composite signal. This output may range over the entire 500 kc/s signal bandwidth of the magnetometer. However, the signal processor described below maps the 500 kc/s spectrum into a single band approximately 100 kc/s wide, providing an amplitude-stabilized and filtered output sinusoid whose frequency is the difference in magnitude between the Larmor frequency and that multiple of 100 kc/s which produces a difference frequency 100 kc/s or less and lying in the proper sideband. Effectively, then, the original 500 kc/s band is "folded" into a 100 kc/s space. (A few hundred cycles per second at the low end are excluded.)

4. Each instrument meets or exceeds the thermal and mechanical environmental specifications set forth in Exhibit "A" to Purchase Request 146590.

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[2] Ibid. Also see AFSWC TN 60-15, "Rocket-Borne Magnetometer Development Program," June, 1960. (Unclassified).

III. MAGNETOMETER SYSTEM DESCRIPTION

The physical principles underlying magnetometer operation have been described.[3] Inspection of Figure 3, the system block diagram, shows that this system consists of two complete dual-gas-cell instruments which have been coupled together, their output signals being combined in the signal processor. Figure 1 is an overall view of the magnetometer system; the two lamps and some covers have been removed to show detail. Figure 2 pictures all the assembled units (one lamp has been removed from the sensing head).

A sensing head assembly is shown in greater detail in the photograph of Figure 4. The axes of the dual-cell sensors are 45 degrees apart: if one sensor is in a dead zone due to its alignment with the measured field vector, the other sensor will be oriented to produce a signal. Usually, both sensors are producing signals simultaneously, although there remain narrow dead zones in which neither sensor produces a useful signal. Note in the block diagram (Figure 3) that the two instrument halves are locked together in the proper phase by connection between two of the four driving fields.

The key system elements will be described in detail, particularly when they differ substantially from the corresponding elements of the dual-cell magnetometer previously described.

A. LAMP OSCILLATOR

These units, shown in Figures 1 and 2, are very similar to their counterpart in the dual-cell instrument. Each provides about 1 watt of power at a radio frequency which can be adjusted between 120 Mc/s and 135 Mc/s, approximately. Plate voltage and ac-heater current for the two subminiature vacuum tubes in each oscillator are supplied by the power converter and regulator (described below). In operation, the two lamp systems are tuned to frequencies at least 4 to 6 Mc/s apart so that their beat frequency will not be passed by the broadband signal amplifiers. Suitable bypassing and shielding are necessary to prevent phase distortion in the signal amplifiers due to detection of either lamp oscillator frequency.

Each oscillator will supply sufficient power to operate a lamp through as much as 12 feet of intervening coaxial cable.

B. LAMP ASSEMBLY

An enlarged view of a lamp assembly may be seen as Figure 5. The bulb heaters (not visible in the photograph) and the components terminating the coaxial line

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[3] See Report No. AFSWC-TDR-62-25

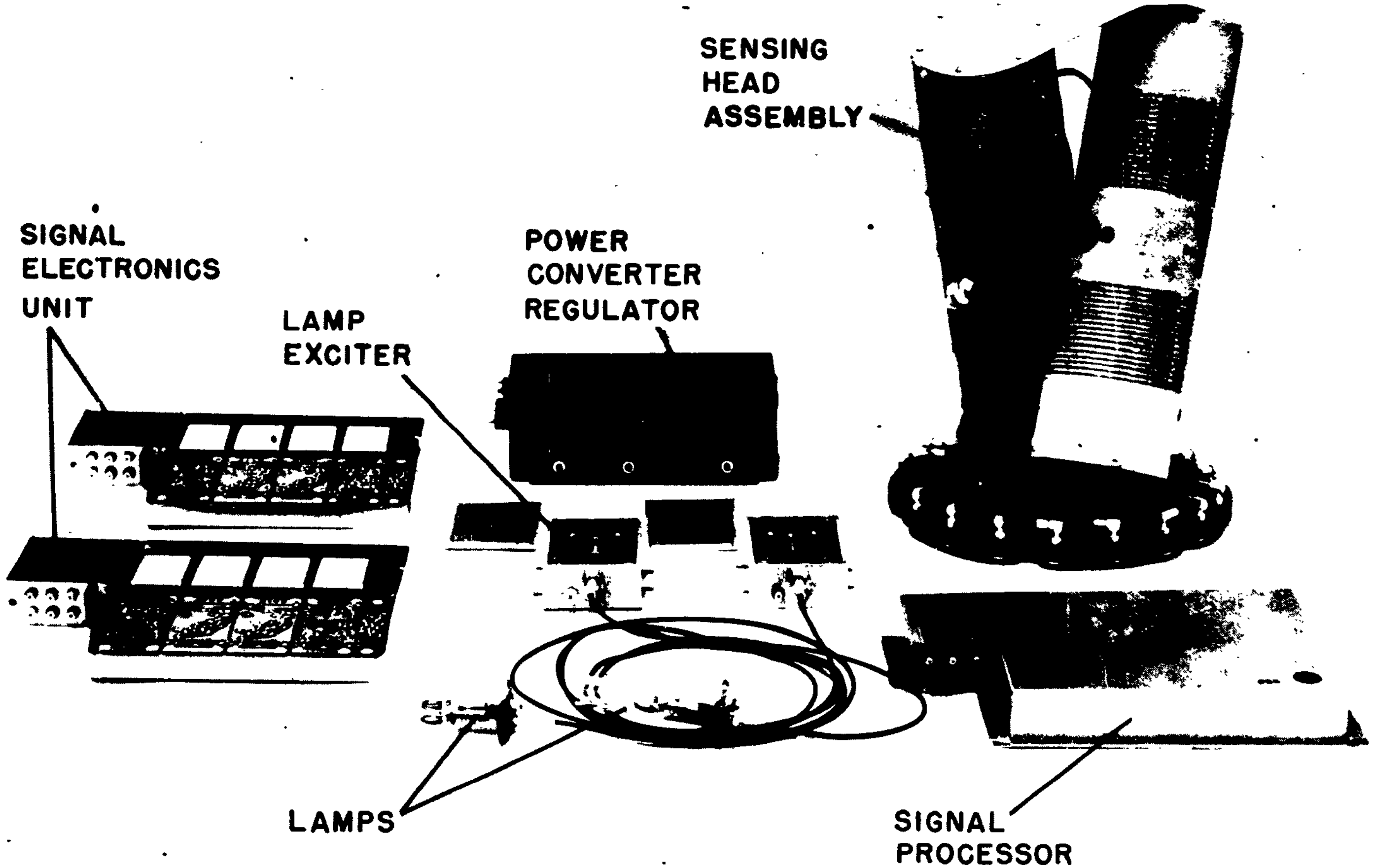

FIGURE 1
MAGNETOMETER SYSTEM (UNCASED)

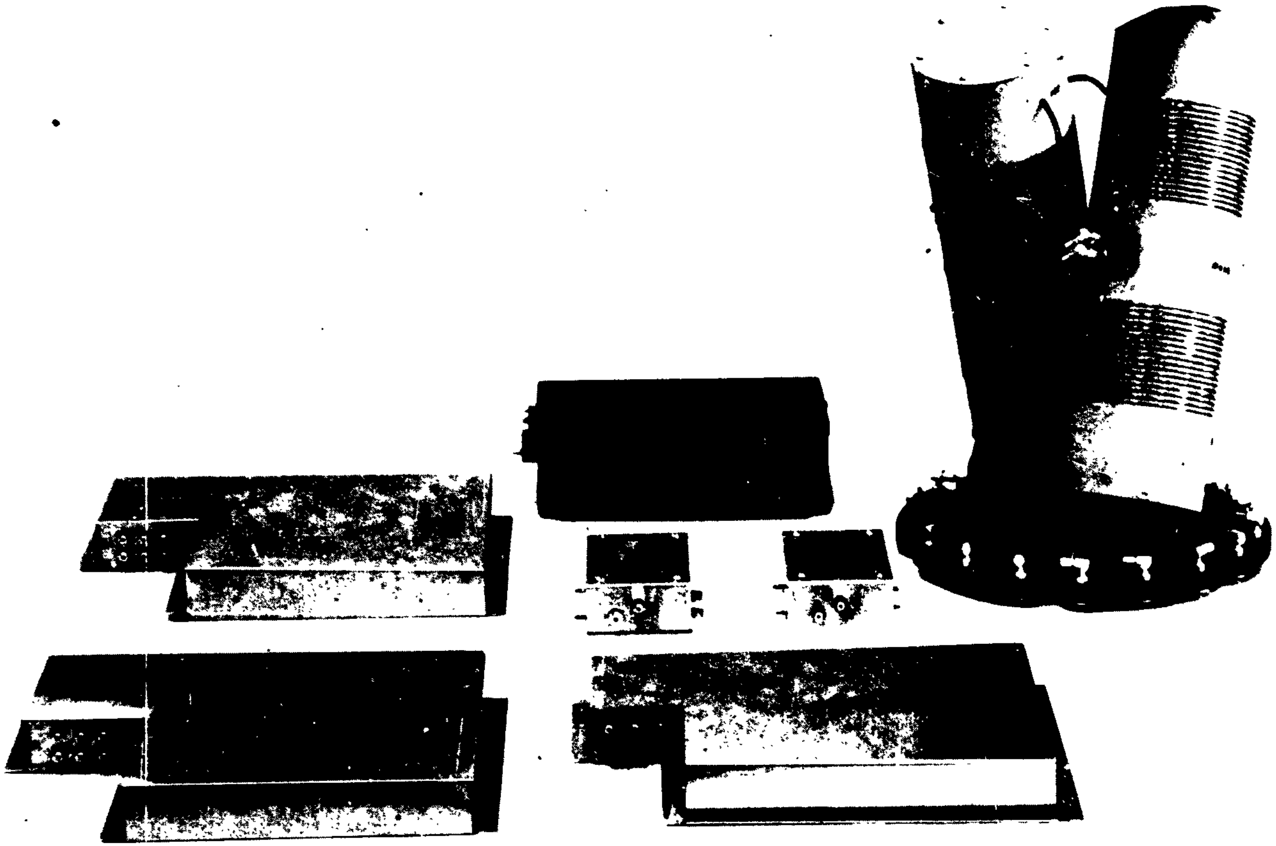

FIGURE 2
MAGNETOMETER SYSTEM

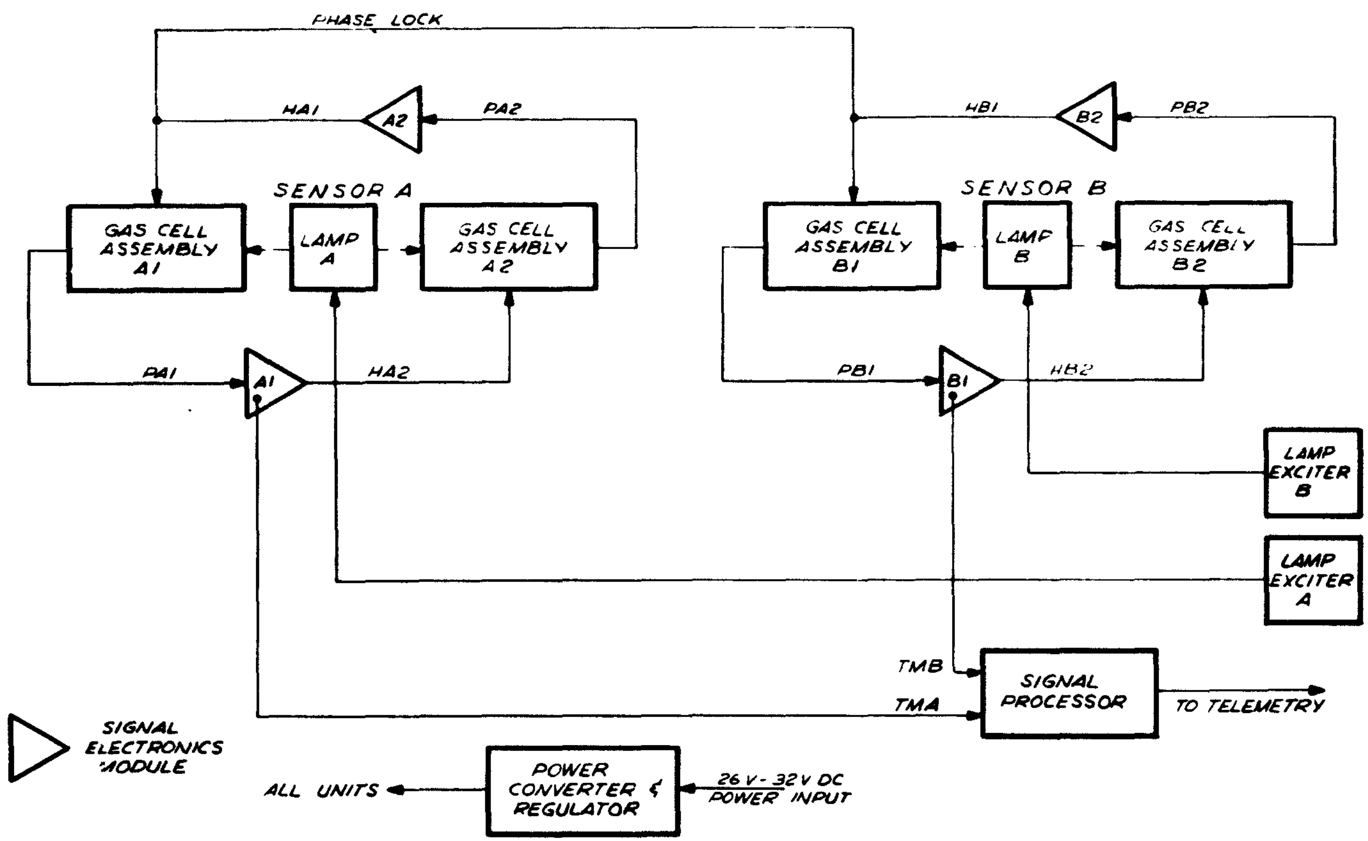

FIGURE 3
MAGNETOMETER SYSTEM BLOCK DIAGRAM

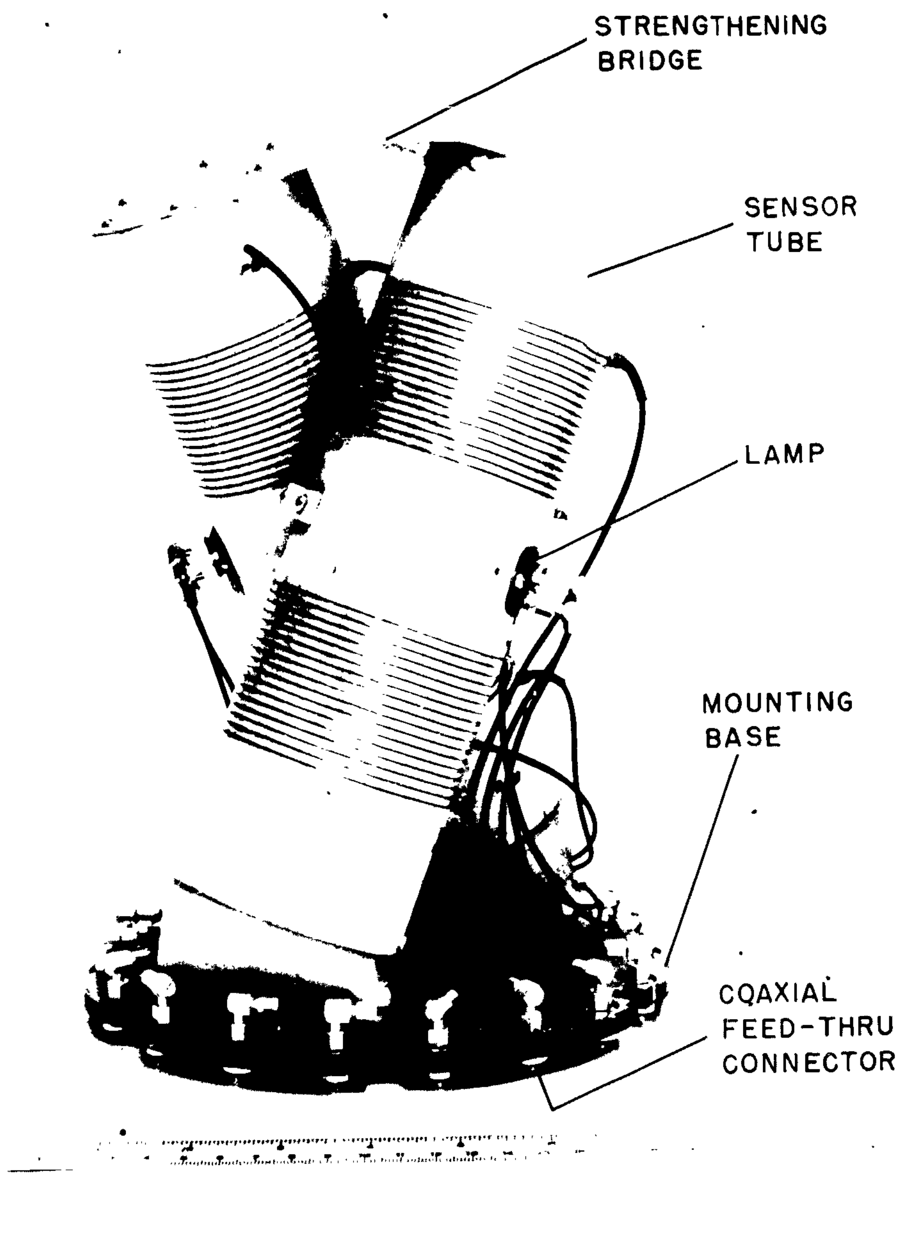

FIGURE 4
SENSING HEAD ASSEMBLY

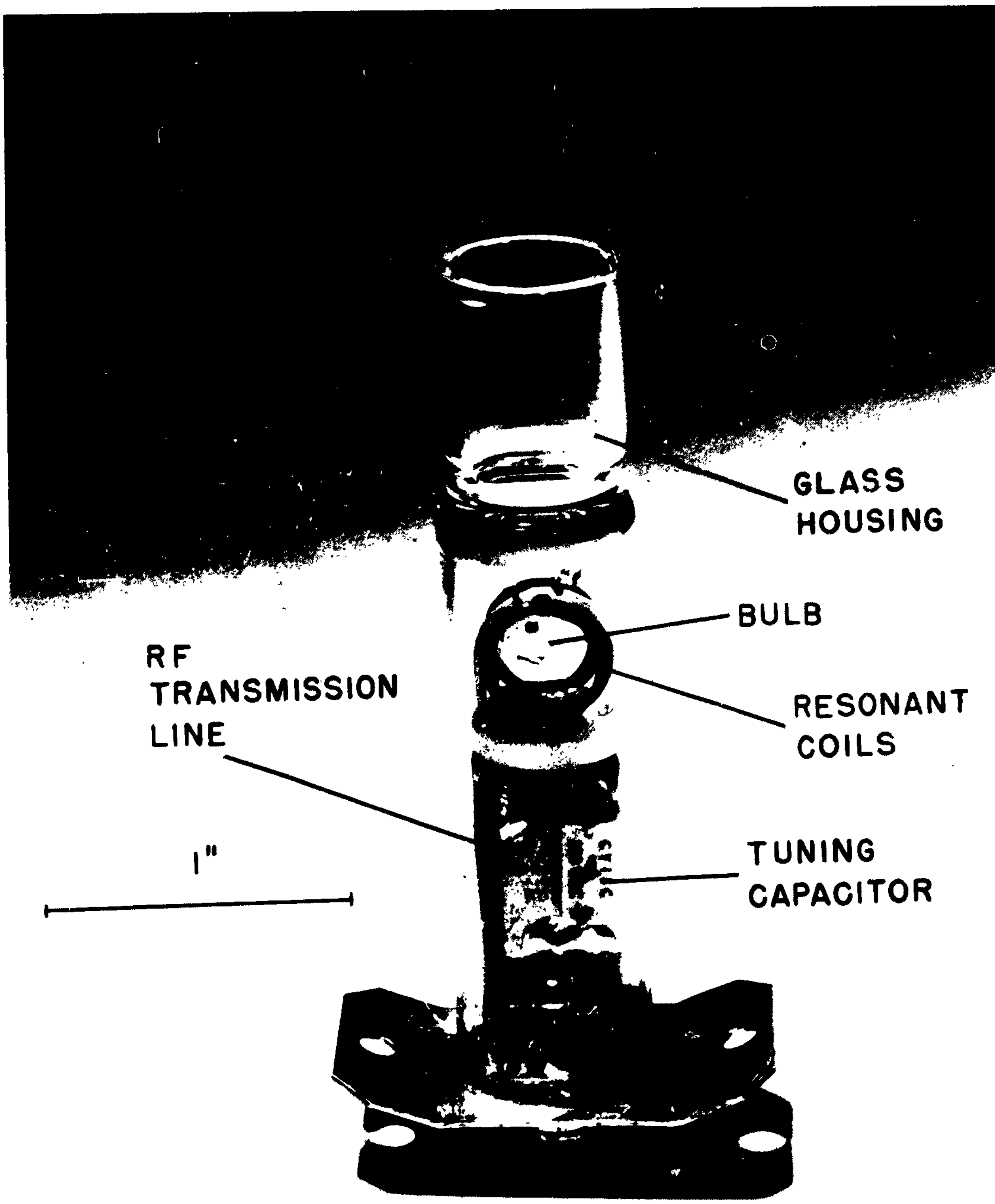

FIGURE 5
LAMP ASSEMBLY

are mounted on an etched circuit card. This unit is sealed inside the glass envelope, so that the trapped air may provide a stable thermal environment regardless of pressure outside the enclosure. The transmission line and the heaters are terminated in coaxial connectors. The heaters are constructed and placed geometrically to minimize any magnetic effects of the small direct currents flowing through them.

C. SENSING HEAD ASSEMBLY

An exploded view of one of the two dual-cell sensors is shown in Figure 6. Only the major components are shown here, and it may be noted that an uncased model of the lamp is pictured.

Bifilar-wound heaters for the gas cells are interleaved with the inner H_1 (driving field) windings. The unit heaters in each sensor half are parallel-connected internally; the two sensor heaters are series-connected externally in the small copper box which can be seen on the mounting base in Figures 1 and 2.

The outer sensor tube carries a second part of the H_1 winding for each gas cell. The two windings for each cell are series-connected, the arrangement being necessary to prevent electrical interference between H_1 fields on the adjacent sensors.

Care has been taken to eliminate as much metal as possible from the vicinity of the gas cells in order that field distortion due to eddy currents may be minimized.

Each sensor is placed in proper orientation to the base plate by means of a laminated epoxy-glass cup whose design permits good transfer of stresses from the sensor tubes to the base plate. The sensors are joined at the top by a laminated "bridge" which acts as a stiffening member. The base plate also serves to mount the necessary coaxial connectors to rigidly terminate and strain-relieve the various cables serving the sensing head assembly.

Although this sensing head assembly has passed full mechanical environmental tests when mounted on the base plate as described, each flight unit was fully potted in a low density (2 lbs/cu ft) polyurethane foam. The foam restrains cable movement, strengthens the assembly and provides an improved thermal environment for the gas cells and lamps.

D. PHOTODETECTOR

Two views of a photodetector assembled on an etched circuit card and a fully assembled unit are shown in Figure 7. The four silicon p-n junctions, each 5 mm square, are series-connected to reduce net capacitance and in such a manner that noise pickup is reduced. The junctions are coated with an inert transparent resin to prevent contamination of the junctions.

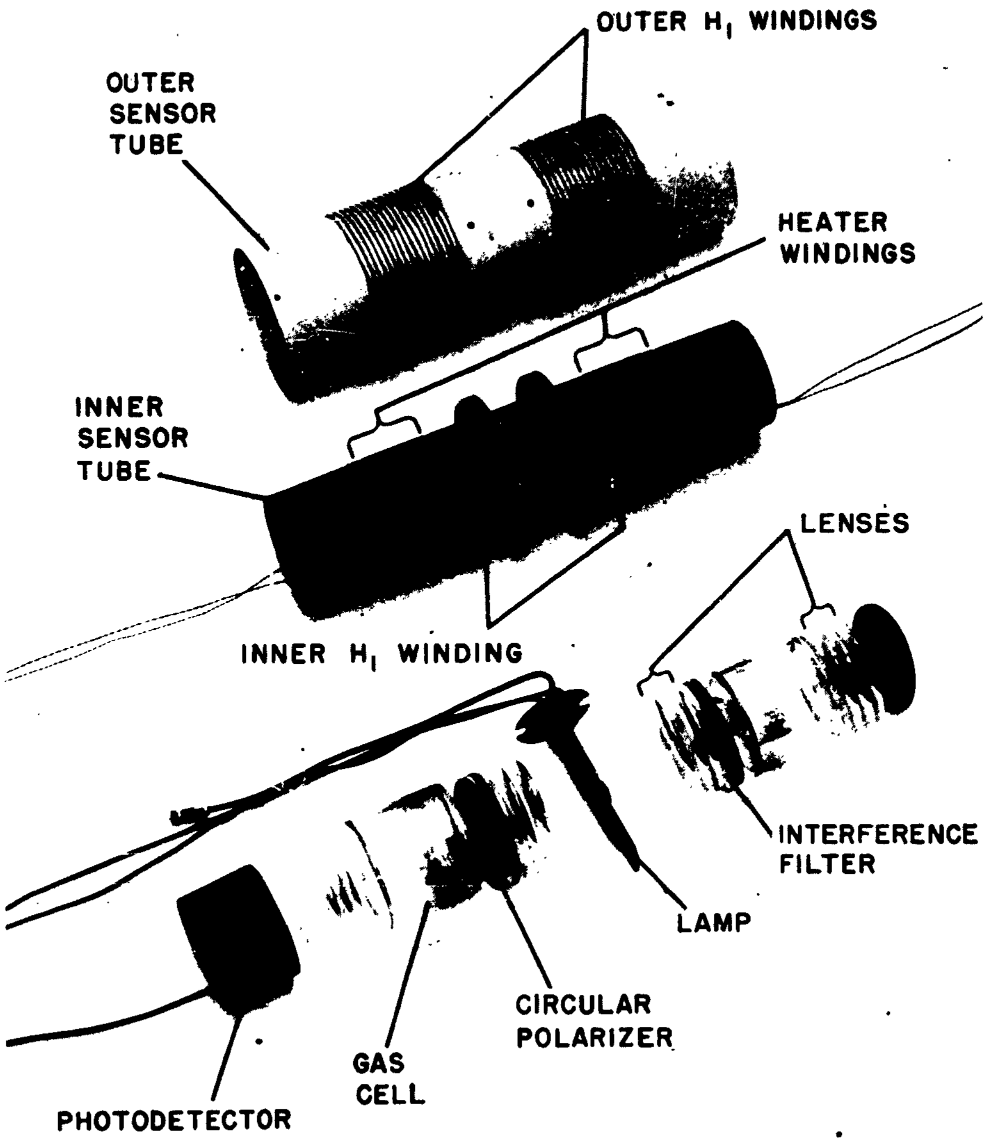

FIGURE 6
SENSOR: EXPLODED VIEW

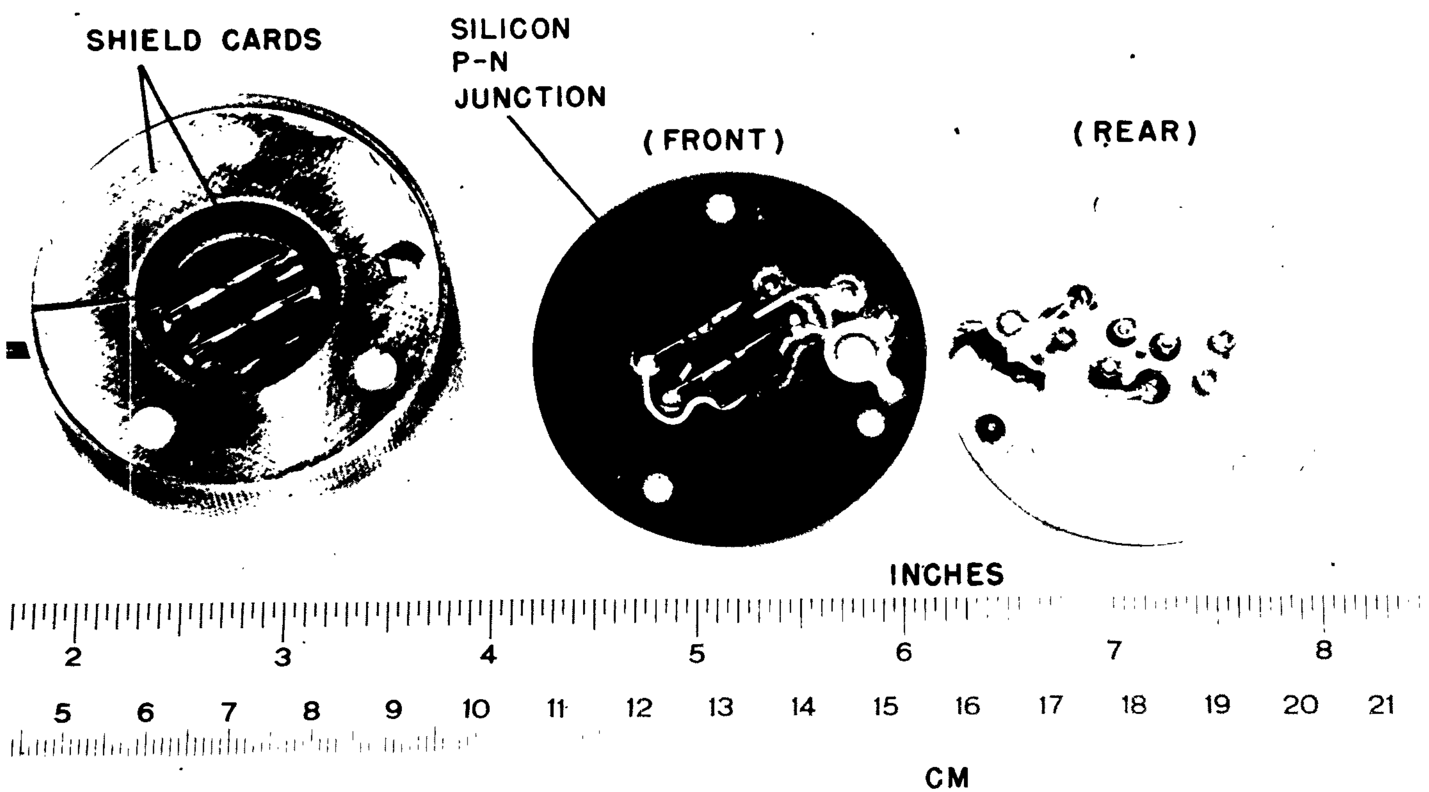

FIGURE 7
PHOTODETECTOR DETAILS

E. SIGNAL ELECTRONICS

As in previously-described instruments[4] and as shown in the block diagram of Figure 3, the driving field for each gas cell is supplied by passing current through a coil (or coils) surrounding the cell. The current, varying at the Larmor frequency, is derived from the photodetector output. The phase of this current, relative to the light intensity fluctuation sensed by the photodetector, must be controlled precisely over the system bandwidth. Since the present magnetometer system consists of two coupled dual-cell magnetometers, each of the four signal electronics units must provide a coil current of controlled amplitude (to prevent broadening the resonance of the optically-pumped systems) and in phase with the light modulation from which it is derived.

The various subassemblies comprising a signal electronics unit are pictured in Figure 8. Here it can be seen that two units are mounted in one housing, a "unit" consisting of a phase compensator, two unit amplifiers, a signal limiter/buffer, and a voltage regulator. Each functional section is assembled on an etched-circuit card of a standard size and shape. The signal-carrying units are individually shielded on their component sides. The shield cans also serve as molds for the application of polyurethane foam to protect components from the effects of shock and vibration. The entire case is potted in foam as well, securing the wiring within the box.

A schematic diagram of the two signal electronics units housed in the box of Figure 8 is presented in Figure 9. Note that Amplifier No. 2 is identical to No. 1, except for the addition of Q23 and associated components; this is the signal buffer stage (to be described), only two of which are needed per system.

1. Phase Compensator

Transistor Q1 has an input impedance of 200 ohms or less, adjustable by selection of resistors R7, R9, and R11. This impedance is kept low to reduce phase shift occurring at the photodetector; the small inductance L1 provides some compensation around the first stage. Further compensation of photodetector phase shift is achieved at Q3 by L3, where R19 and R25 provide a further gain and phase adjustment. The "Q" of L1 and L3 must be lowered (by R5 and R21, respectively) to prevent excessive gain at the higher signal frequencies. As loaded by the following unit amplifier, the phase compensator is capable of zero-phase-shift performance from 100 c/s to 500 kc/s. Its voltage gain is set at approximately 48 db.

2. Unit Amplifier

If the open-loop gain of a servo system exhibits phase lag, closed-loop lag can be reduced to zero by introducing a controlled amount of lag in the system's negative

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[4] *Ibid.*, pp. 3-6.

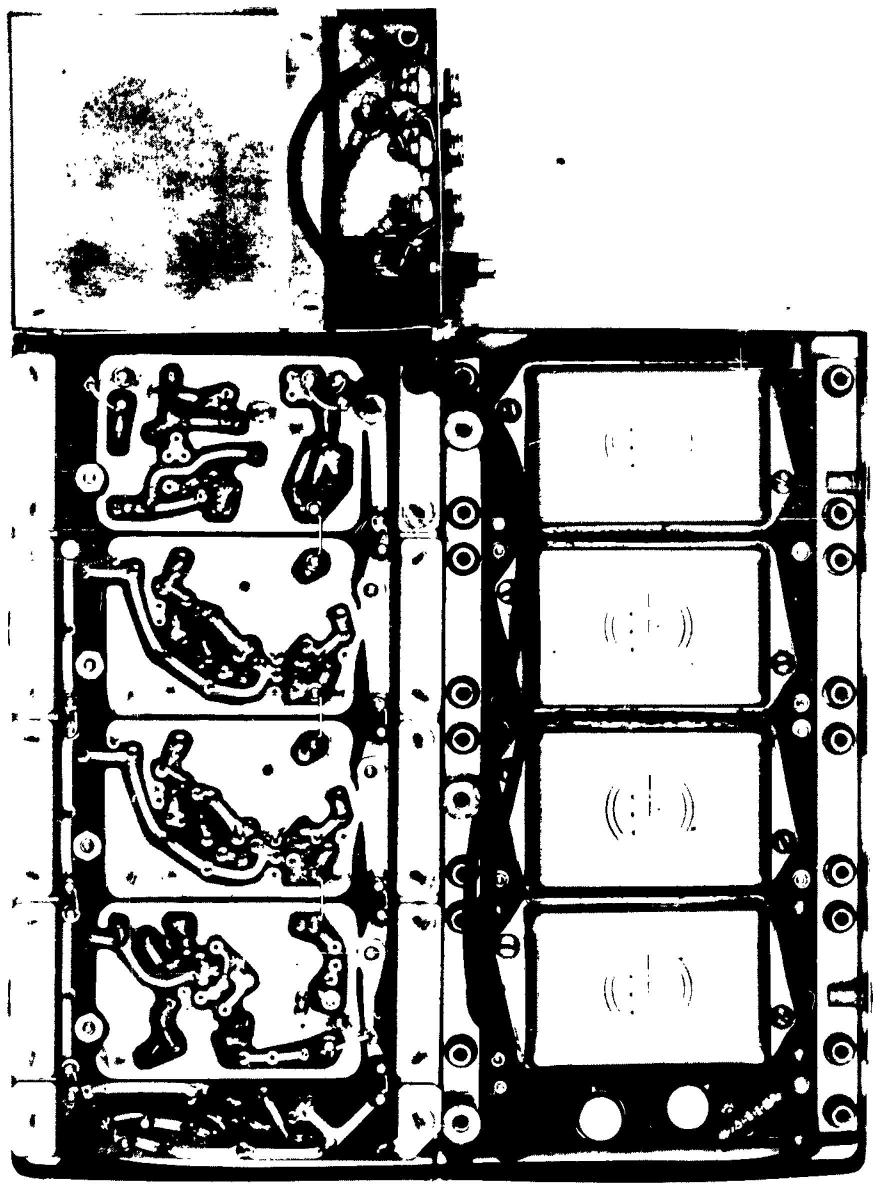

FIGURE 8
SIGNAL ELECTRONICS UNIT (UNCASED)

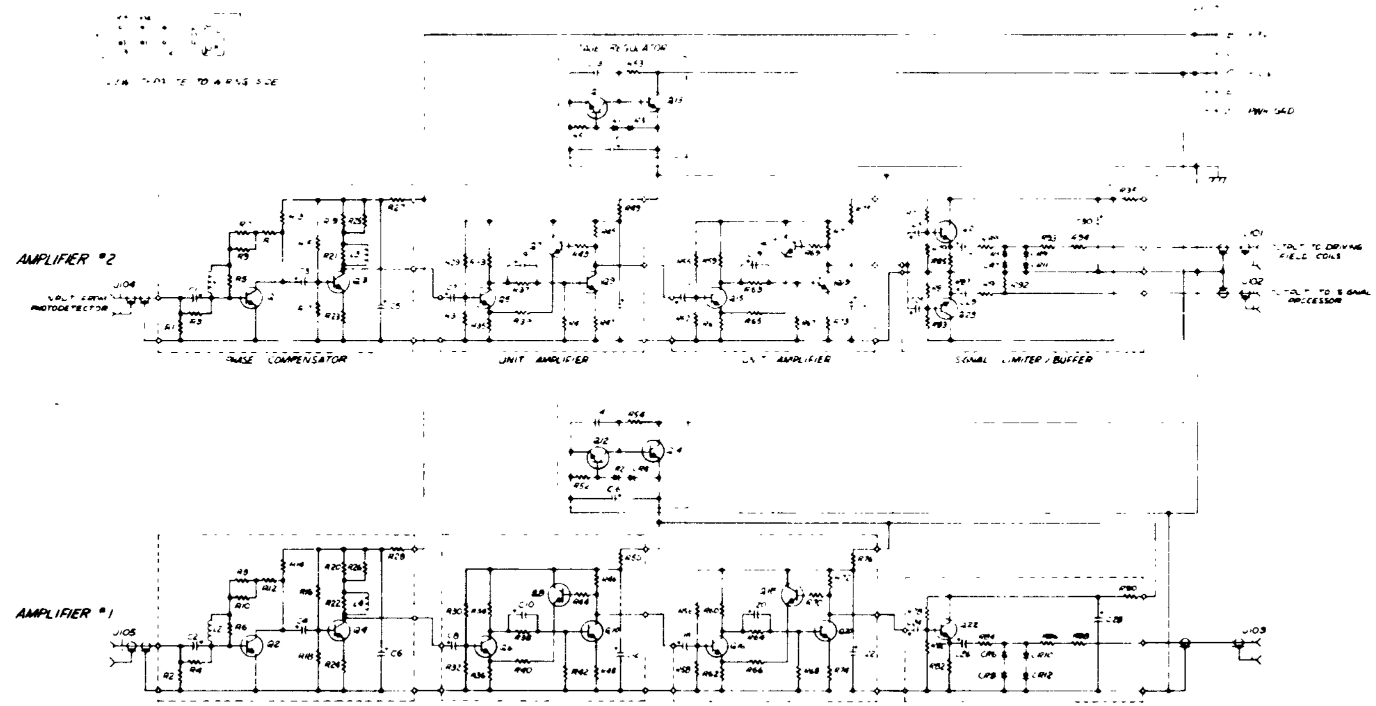

FIGURE 9
SIGNAL ELECTRONICS SCHEMATIC DIAGRAM

feedback network.

Thus, the amplifying stages of a unit amplifier, characterized by Q5 and Q9, add time delay to the amplified signal; this is an effect similar to the introduction of relatively large electron transit times within a vacuum tube. The delay accounts for a large amount of amplifier-introduced phase shift at frequencies above approximately 200 kc/s.

To reduce the time delay to zero, a transistor "poor" enough to produce a relatively large delay is placed in the negative feedback loop between Q9 and Q5. This is Q7, whose delay is much greater than that of Q5 and Q9 combined. The resistors R37 and R43 provide a small phase adjustment and, together with the presence in the loop of Q7, are made to contribute to stability of gain and phase at ambient temperatures as high as 60 degrees C.

Each unit amplifier is adjusted to provide a voltage gain of approximately 32 db over the 500 kc/s signal band.

3. Signal Limiter/Buffer

The emitter-follower Q23 in Figure 9 ac-couples a high-level output signal from the output of the second unit amplifier to the attenuating network comprised of R91 and R92. These resistors are paralleled by an equal impedance in the opposite sensor's output circuitry; the four resistors and two emitter-followers thus set the impedance and (mixed) input signal level seen by the signal processor.

A second emitter-follower on this circuit card, Q21, buffers the signal limiters CR5, CR7, CR9, and CR11 from the other circuits. These diodes are chosen for low junction capacitance at low bias; they limit upon forward conduction. They are provided in matched sets to eliminate any net direct current which would otherwise flow through the driving field coils, seriously distorting the measured field, particularly at low intensities. The diodes are series-connected in each pair to provide a higher clipping level for the signal from which the feedback current is metered by choice of R93 and R94. (Note R92, R94, and R88, visible at the output terminals in Figure 8.)

4. Voltage Regulator

In order better to isolate the various high-gain amplifiers comprising the magnetometer system, each of the four signal electronics groups is provided with a voltage regulator on its +12 volt supply. This stabilizes gains against supply changes and provides the desired isolation by virtue of a low-impedance output.

In a typical regulator (see Figure 9), CR1 and CR3 are two zener reference units. Any change of output voltage (occurring across the series combination of R51 and the diodes) is sensed across R51, since the diode reference voltage remains

essentially constant. This error signal is amplified by Q11, appearing as an output across R53 with the necessary reversal in phase. The emitter-follower Q13 provides further power-gain for the error signal; the load (including the voltage reference) is placed in its emitter circuit.

Bypassing for high frequency noise is provided by C13, while C15 increases stability at low frequencies as well.

The regulator output is +9.3 volts with a terminal impedance of less than 2 ohms over a wide frequency range.

IV. SIGNAL PROCESSOR

A. INTRODUCTION

To adapt the magnetometer output signal to the telemetry needs of the experiment, it was necessary to prepare the broadband (500 kc/s) signal for transmission over a 1 kc/s to 100 kc/s channel. Further, the signal-to-noise ratio was to be preserved and the data transmission capability of the 100 kc/s channel was to be used fully.

The fundamental concept employed in solving this set of problems is that of multiplying the raw data fluctuations by a time function which has a near-constant intensity line spectrum, and then selecting the lowest frequency modulation product. Most simply, the raw data might be sampled with a narrow 200 kp/s pulse; the portion of the sampler output spectrum lying below 100 kc/s would be transmitted. An elementary block diagram of such a system, together with a representation of its response characteristic, is shown in Figure 10. The sampling pulse, in this case, has a duty cycle of 1/7 so that the $(\frac{\sin x}{x})$ - type sampling spectrum has a null at 7 x 200 = 1400 kc/s, but holds up past the 800 kc/s mark. Data inputs in the neighborhood of (2 n + 1) x 100 kc/s will produce two output frequencies, mirrored about 100 kc/s.

A plot of the frequency of significant components of the transmitted data as recovered from the signal processor might appear as does the solid line in Figure 11. Reconstruction of the original data depends upon rough knowledge of the initial signal conditions characteristics. The dashed line in Figure 11 is a reconstruction of the original data in the example, on the basis that the initial frequency was within $\pm$ 100 kc/s of 400 kc/s and that it will increase initially. At every point where an ambiguity exists, the initial portion of the possible alternate plot has been indicated.

B. LOSS OF DATA

So long as the data phase acceleration is low enough that it can be reproduced within a 100 kc/s passband, no detailed data is lost. An unavoidable cost of bandwidth reduction is the ambiguity regarding gross features of the data. If the simple low-duty-cycle pulse were employed as the multiplying function (as in the example above), there would be a second inevitable cost: a reduction in signal-to-noise ratio.

A 5 μs (i.e., one period of 200 kc/s) interval of the data input may be considered to consist of seven samples of the data sinusoid plus wideband noise. If all of the samples in a sequence of 5 μs intervals are applied to a narrow-band filter which is being adjusted in an attempt to define the data frequency, it will be found that the noise content of the samples (being independent) combine on a root-sum-square basis, whereas the signal content combines on a sum basis. If only one of the samples per period is employed, then signal and noise compete on an equal footing and a $\sqrt{7}$:1, or 4.2 db, loss in signal-to-noise ratio is incurred.

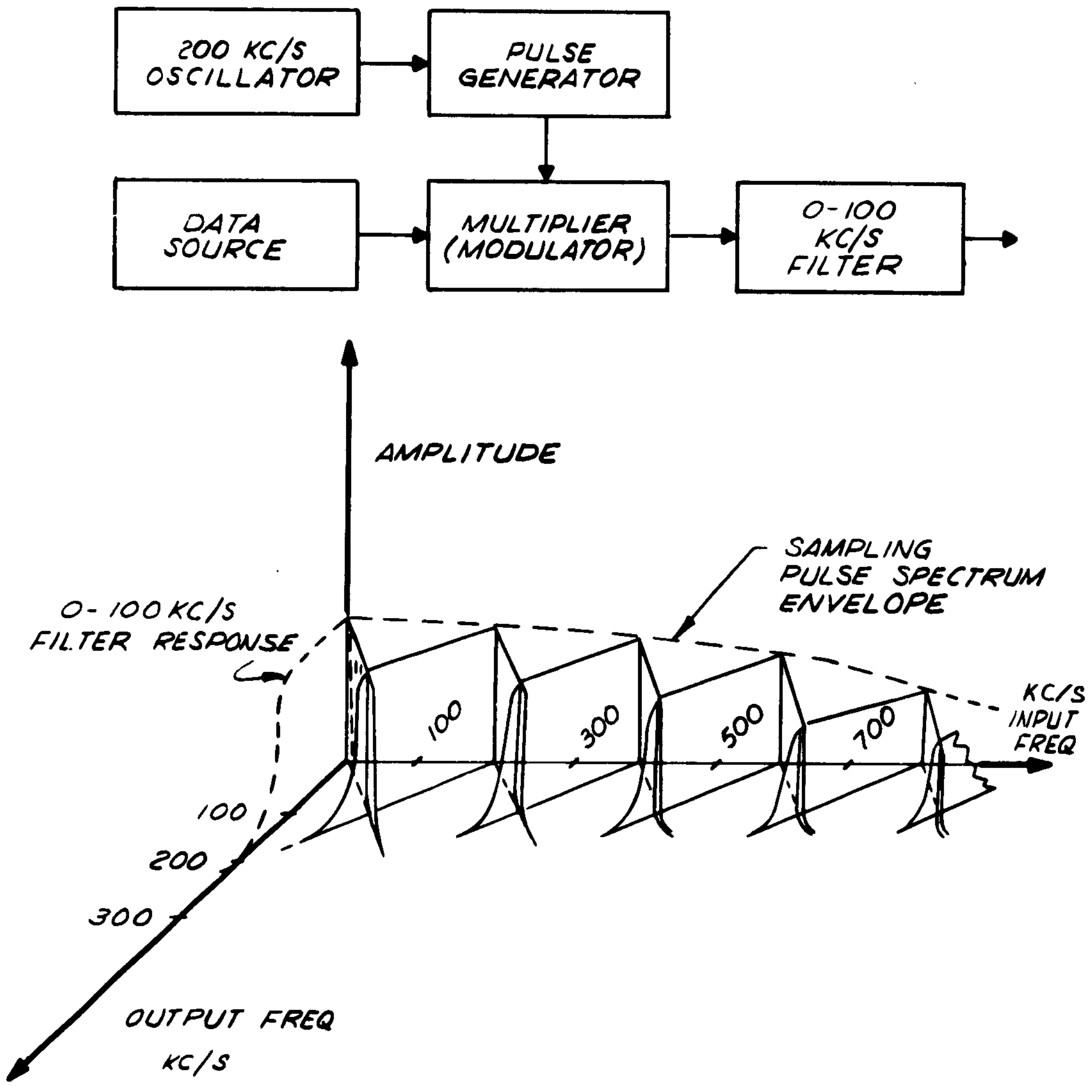

FIGURE 10
SIGNAL PROCESSOR RESPONSE

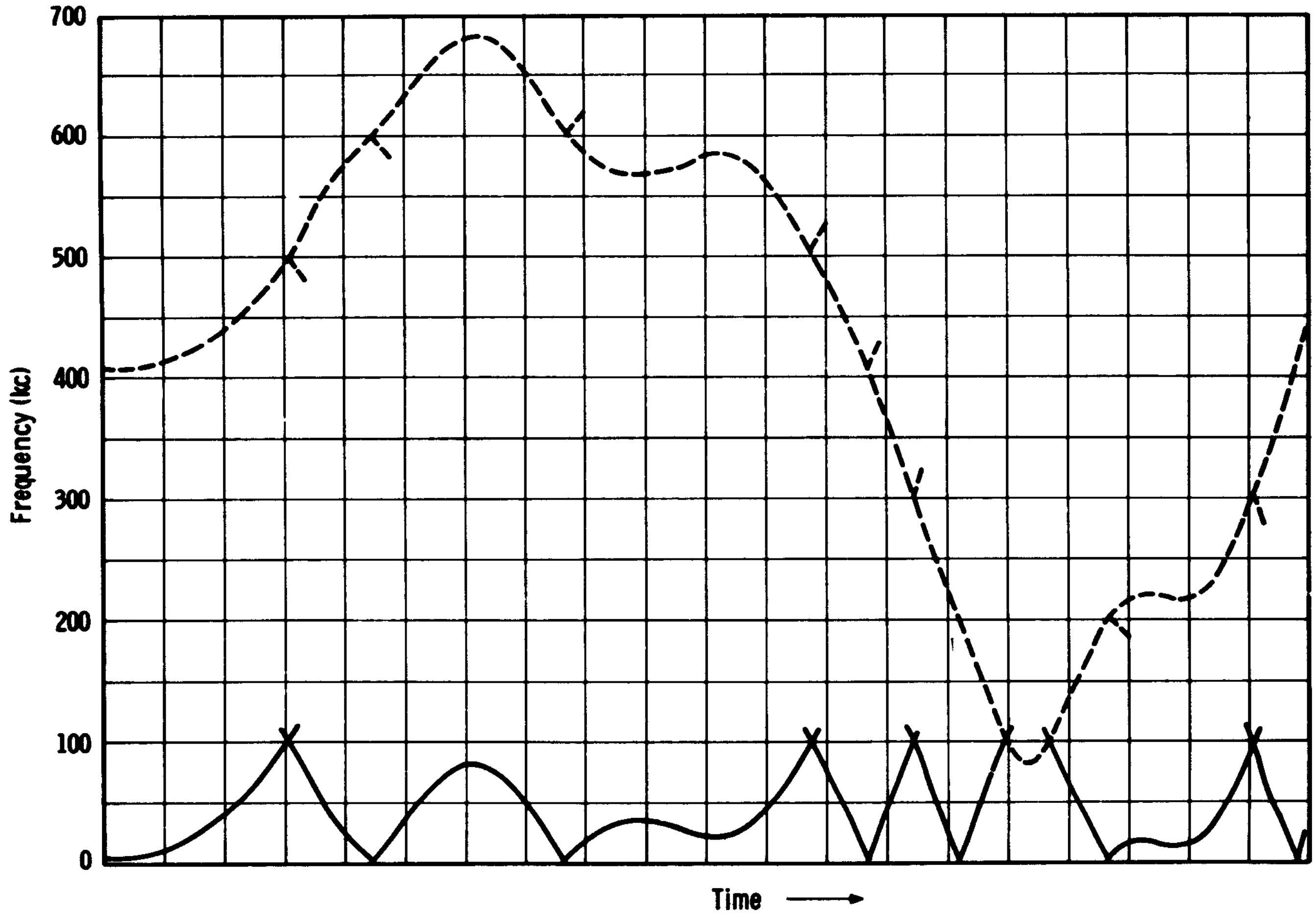

FIGURE 11
DATA RECOVERY EXAMPLE

C. GENERATION OF THE MODULATING FUNCTION

The kind of modulating function sought, therefore, is one which gives equal weight to all samples but which combines them in such a way as to give the frequency-conversion characteristics of the simple pulse. The code selected[5] may be written: 1011000, in conventional binary notation. A sequence of pulses corresponding to this code can be produced by driving a constant-resistance lattice with a narrow pulse. The driving pulse is generated by a blocking oscillator keyed to a 200 kc/s crystal oscillator, producing a 200 kp/s output with a duty cycle of 1/7. A transversal filter realization of the code-producing lattice is indicated in Figure 12.

The highest useful harmonic of the 200 kp/s driving source is the seventh, 1.4 Mc/s, because of the use of a seven-element code. To pass only this and lower frequencies and to buffer the coding network and the pulse generator, a low-pass filter is employed; see the block diagram of Figure 13.

D. DATA SAMPLING

The coded sampling pulses are presented to a ring modulator, along with the sampled data; see Figure 13. The output of the modulator, consisting of all the modulation products of these two signals, is then passed through a low pass filter, which allows only those components lying at 100 kc/s and below.

The filter output is buffered by an emitter follower, reducing any effects of external loading on the signal processor circuits.

E. CIRCUIT DESCRIPTION

A schematic diagram of the signal processor is shown in Figure 14. As indicated, four modules are interconnected to form the complete assembly.

Module I contains the 200 kc/s crystal oscillator, buffer amplifier, and blocking oscillator. The crystal oscillator consists of the two-stage common emitter amplifier Q1 and Q2, the crystal Y1 being used as a series-resonant element to close a positive-feedback path around the amplifier. Oscillator output is limited by operating Q1 and Q2 at low collector voltages. The network L1-C3 provides a degree of frequency selectivity to the open-loop amplifier characteristics, preventing crystal operation at a spurious frequency.

The buffer stage Q3 isolates the crystal oscillator from the heavy loading of the blocking oscillator Q4-T1. Diode CR1 makes the input waveshape approach the

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[5] Such codes can be found for sequences of 2^n-1 bits. See Huffman, D. A., The Synthesis of Linear Sequential Coding Networks (Second London Conference on Information Theory, Colin Cherry, ed.; New York: Academic Press, 1956).

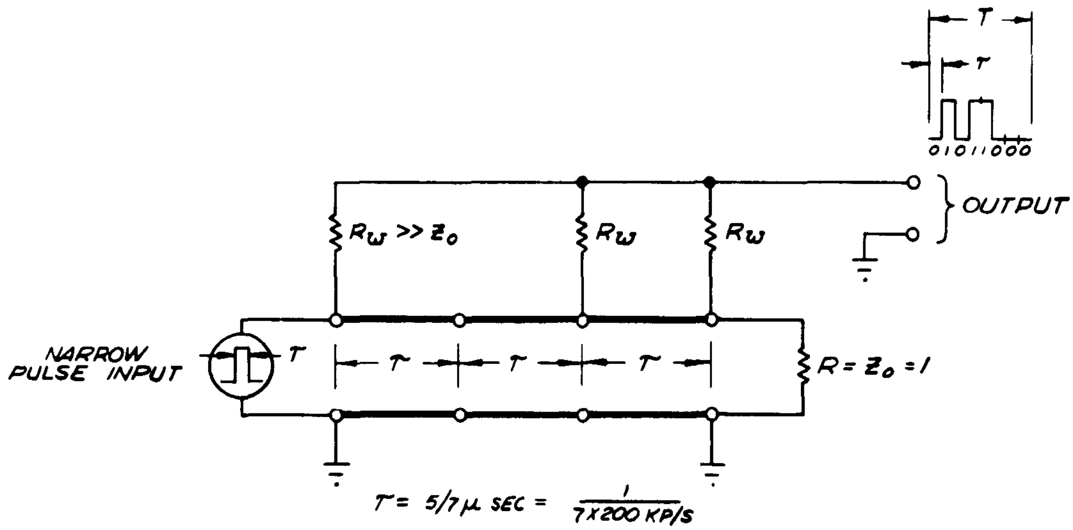


FIGURE 12
CODE-PRODUCING NETWORK

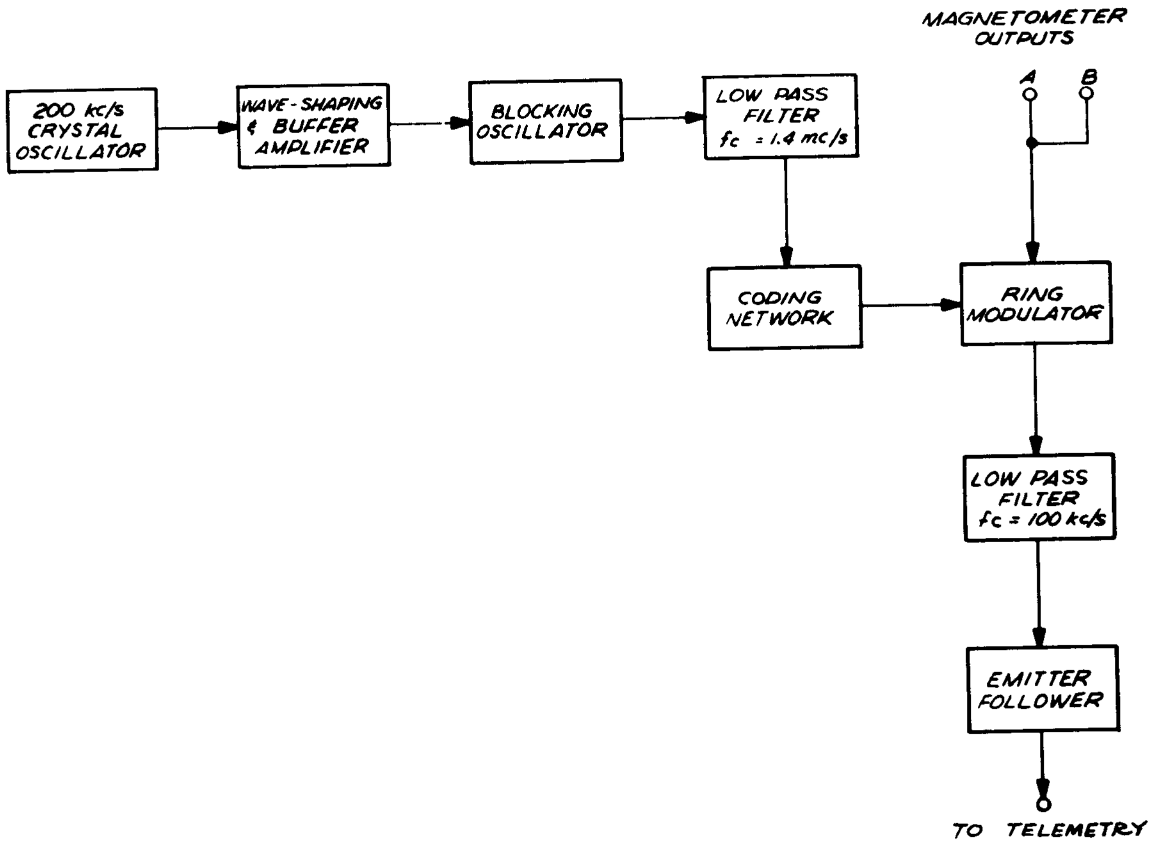


FIGURE 13
SIGNAL PROCESSOR BLOCK DIAGRAM

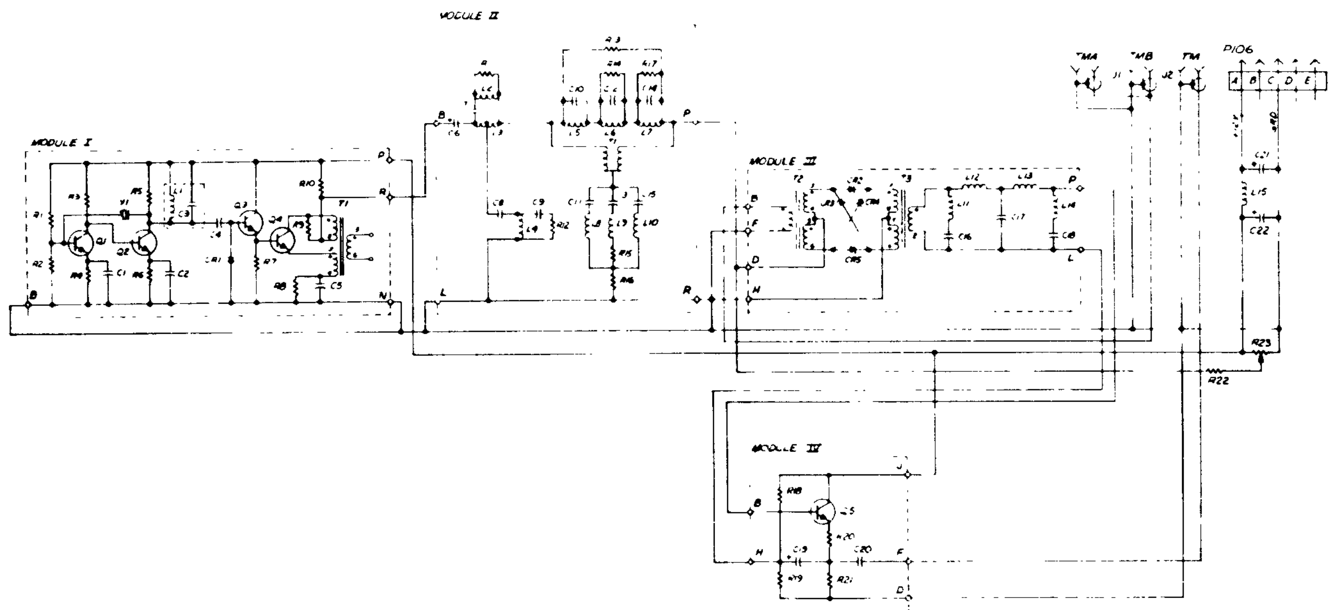


FIGURE 14
SIGNAL PROCESSOR SCHEMATIC DIAGRAM

ideal positive-pulse trigger waveform.

Design effort was concentrated on T1 and associated components to make the blocking oscillator perform well over a wide temperature and supply voltage range, providing dependable triggering from a varying-level source as well as the proper output pulse width and shape. Resistor R9 is chosen to minimize circulating current through the collector winding after turnoff, hence reducing the residual core flux and allowing the oscillator to be more easily triggered in the 10 μs to 20 μs interval after turnoff. Resistor R10 is chosen to improve the waveform, and the drive source is arranged to follow the dc supply, rather than being tied to a fixed value.

Module II contains the low-pass filter seen in the block diagram of Figure 13 following the blocking oscillator; the pulse coding network is also found here. The filter components are associated with L2, L3, and L4, while the pulse coding network consists of the remaining module elements.

Module III consists of the input and output transformers T2 and T3, respectively, the ring modulator diodes CR2 through CR5, and the low-pass output filter connected to the secondary of T3. Input signals to the modulator are derived from magnetometer output signals presented to "TMA" and "TMB" connectors. The signals from the two magnetometer sensors are therefore mixed at the input of the signal processor. The terminal impedance of both input and output is 200 ohms or less. Modulator biasing current is supplied from the +12 volt supply by R22 and R23 in combination; R23 is adjusted to make system response in the 0-200 kc/s range equal to that in the 200-400 kc/s portion of the output spectrum.

The modulator transformers are wound with a twisted trifilar wire and are characterized by low-level half-power points at 10 c/s and 10 Mc/s.

Module IV is an emitter follower Q5 arranged to provide a balanced output to ground, if desired. As supplied, an ohmic connection is made between input and output grounds, however.

Interference of the 200 kc/s oscillator with external circuits is prevented by the π-section filter comprised of C21, C22, and L15 in the power lead.

V. POWER CONVERTER

Figure 15 is a top view of an uncased and unpotted power converter; the assembled unit can be seen in Figures 1 and 2, while its schematic diagram is shown in Figure 16.

Current from an external power source varying from +26 volts to +32 volts in potential may be supplied to the converter. Diodes CR101 and CR102 (Figure 16) will not conduct if power source polarity is inadvertently reversed. This protects both the power converter and the remaining magnetometer system circuits. Diodes CR104 through CR109 regulate the +3 volt and +12 volt supplies to the signal electronics units and to the signal processor. Diodes CR105 through CR109 derive their current from the +12 volt supply and are operated in their forward conduction mode to provide the nominal +3 volt output. Transistors Q103 and Q104, which drive the saturable core transformer core through windings N3 and N4, are mounted on the anodized aluminum base to improve heat conduction away from the unit; zener diode CR104 and regulator transistor Q101 are mounted on the base as well.

Transistors Q101 and Q102 form a high current gain amplifier and serve as the primary voltage regulator for the switching transistors. Alternating current induced from the primary windings by N5 and N6 is full-wave rectified and compared to the voltage developed across zener diode CR110; the difference between the two potentials drives the regulator transistors. Resistors R105 and R106 allow proper setting of the lamp exciter plate voltage, developed from N8, to +165 volts. Since the error signal to Q101-Q102 is not filtered, considerable reduction in noise and ripple on the voltage presented to Q103-Q104 is effected. Capacitors C101, C102, C109, C110, and C111 are employed to bypass the low-voltage supplies and the converter case to payload ground.

Windings N1 and N2 provide base drive for Q103 and Q104, while C103 and R107 provide proper phase trimming at the switching frequency (about 2 kc/s) to produce clean square waves; R113 insures reliable converter starting under varying load and environmental conditions.

Lamp exciter tube heaters are supplied with 6.3 volts (rms) from N7. The use of ac reduces unwanted magnetic interference due to direct current loops and is more efficient.

An application of a potential exceeding the normal lamp exciter plate voltage to the "Lamp Start" pin B of P103 will cause CR117 to conduct and CR118 to block. The lamp exciters may thus be supplied momentarily with a higher-than-normal plate voltage for lamp starting without damaging the power converter. Capacitor C106 prevents conduction of unwanted rf away from the power converter through the lamp start wire.

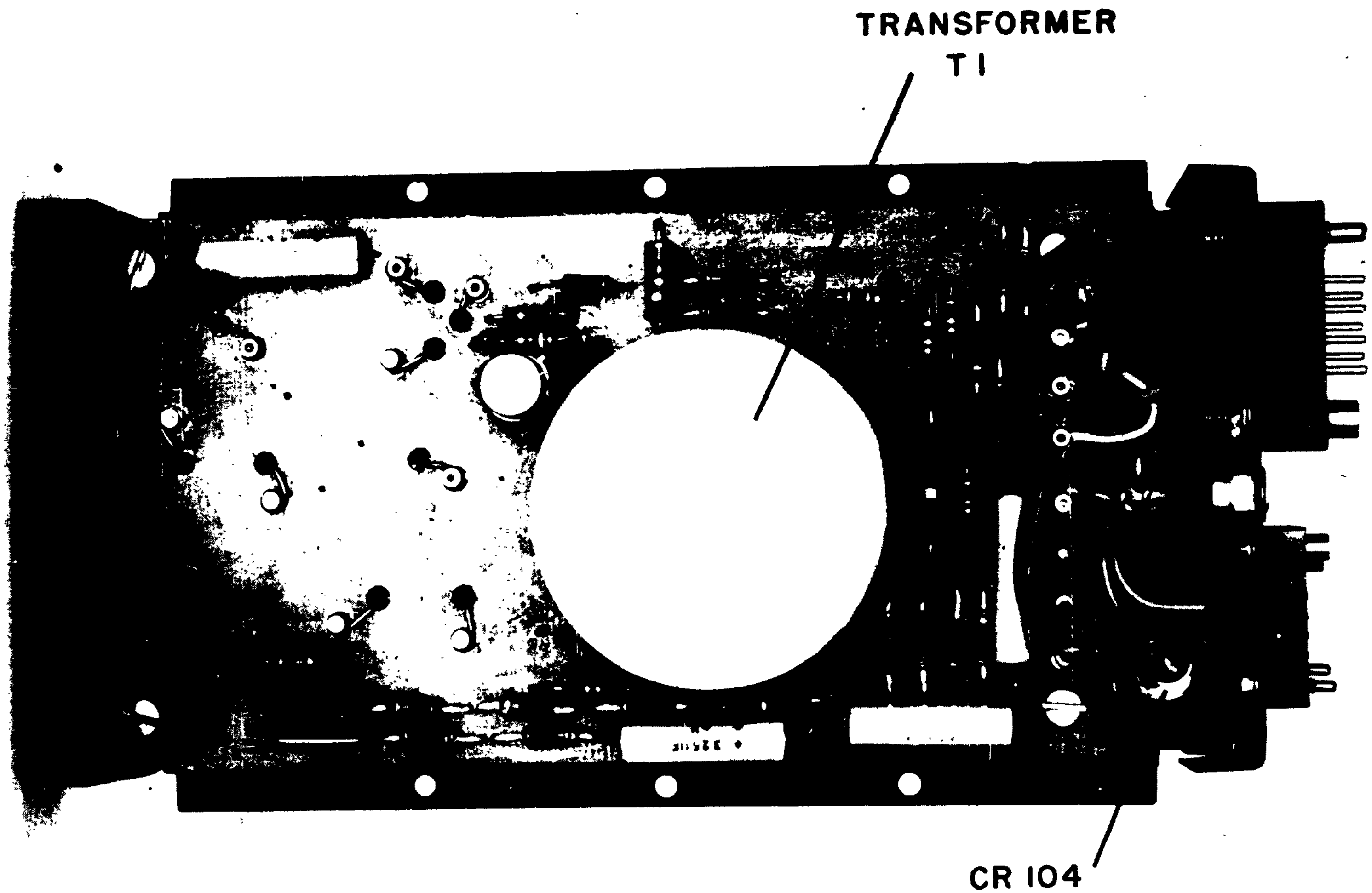


FIGURE 15
POWER CONVERTER TOP VIEW (UNCASED)

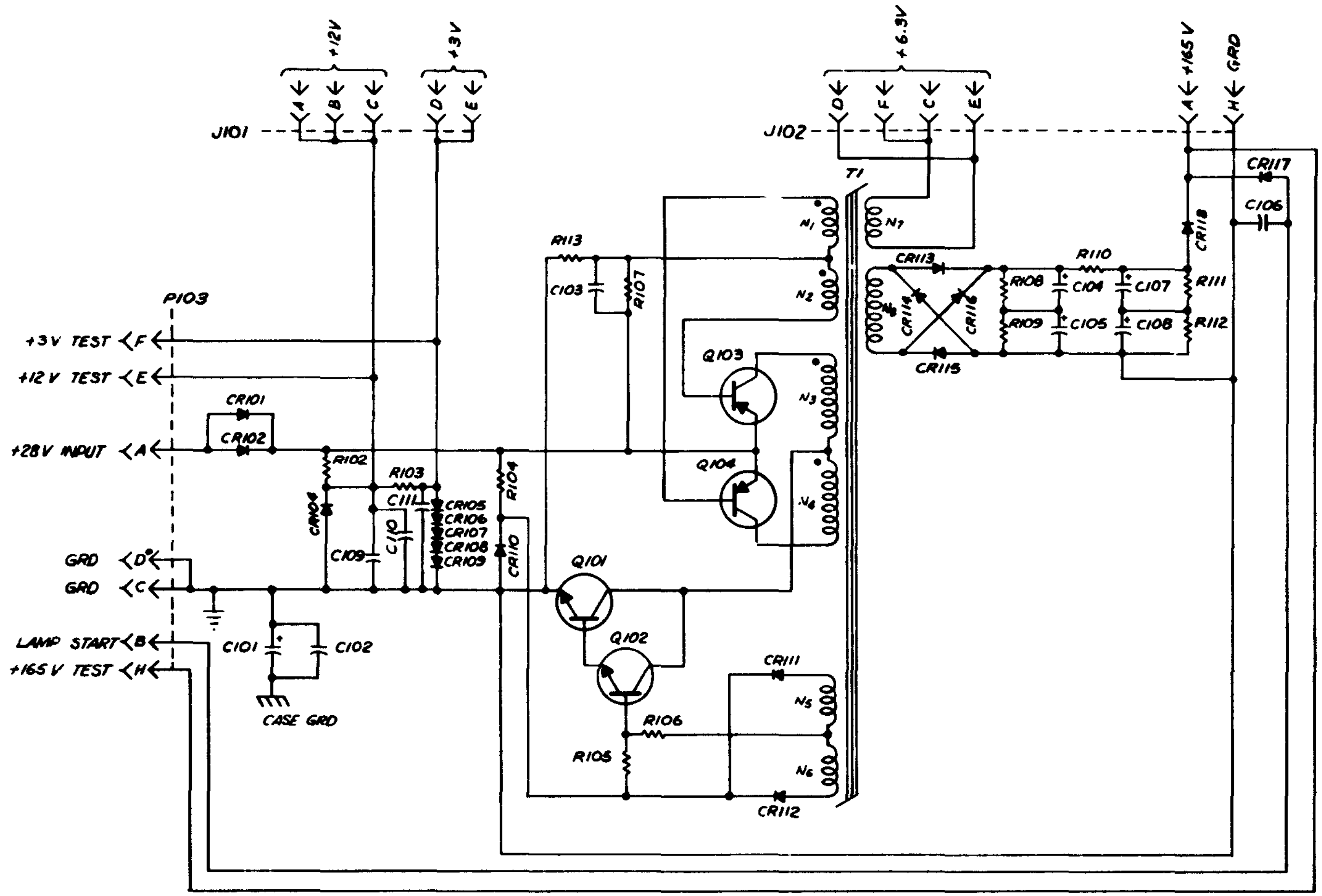


FIGURE 16
POWER CONVERTER SCHEMATIC DIAGRAM

VI. GROUND SUPPORT PANEL

The several elements comprising the ground support panel are shown in the schematic diagram of Figure 17. A temperature controller for the remotely-located gas cells in the magnetometer sensing head, a lamp starter, test jacks, and a power inverter are supplied.

The power inverter, operating from a 12-volt power source (such as a lead-acid storage battery), supplies nominal 117 volts (rms) ac, 60 c/s, to the front panel and to the temperature controller and lamp starter. This allows operation of the panel at a remote site, such as the rocket launching pad; the inverter could be bypassed and commercial 117 volts a-c power used instead, if desired. A fan is supplied to cool the inverter in operation. Note that the inverter power switch S2 has a spring-return "Start" position, which increases base drive to switching transitors Q1 and Q2 by shunting R18 across R19, permitting the inverter to start under a heavy load (such as a cold incandescent lamp). This position of S2 is not normally required, however.

The temperature controller is an ac-bridge in which a control thermistor, remotely located near one of the gas cells, is connected. Adjustable resistances (R1 and R2) are placed in another bridge arm to set the desired control temperature. Bridge unbalance is amplified, the resultant current operating relay K1 whose contacts control the application of 117 volts ac to the gas cell heaters.

The lamp starter is operated by a panel-mounted pushbutton switch S1, which initially closes the primary circuit of T2 while disconnecting the lamp start line from C1 while it is being charged. Charging current, rectified by CR1, is limited by R20. The five series-connected small neon lamps provide voltage regulation to a maximum value of about 325 volts across C1; one of the lamps also serves as a panel-mounted indicator of capacitor charge. When S1 is released, C1 discharges to the lamp starting circuit, placing approximately 300 volts at the lamp exciter tubes' plates for about a second.

Leads from one sensing head thermistor and three power converter voltages are brought to a set of test jacks on the panel and are labelled A through D.

The panel is of standard rack width (19 inches), 8-3/4 inches high, and approximately 7 inches deep.

The interwiring of all magnetometer system elements, including the ground support panel, is shown in Figure 18. All ground leads carrying direct current are made common at the power converter panel. Note also that in addition to the thermistor "GTT" brought to the ground support panel, three high resistance

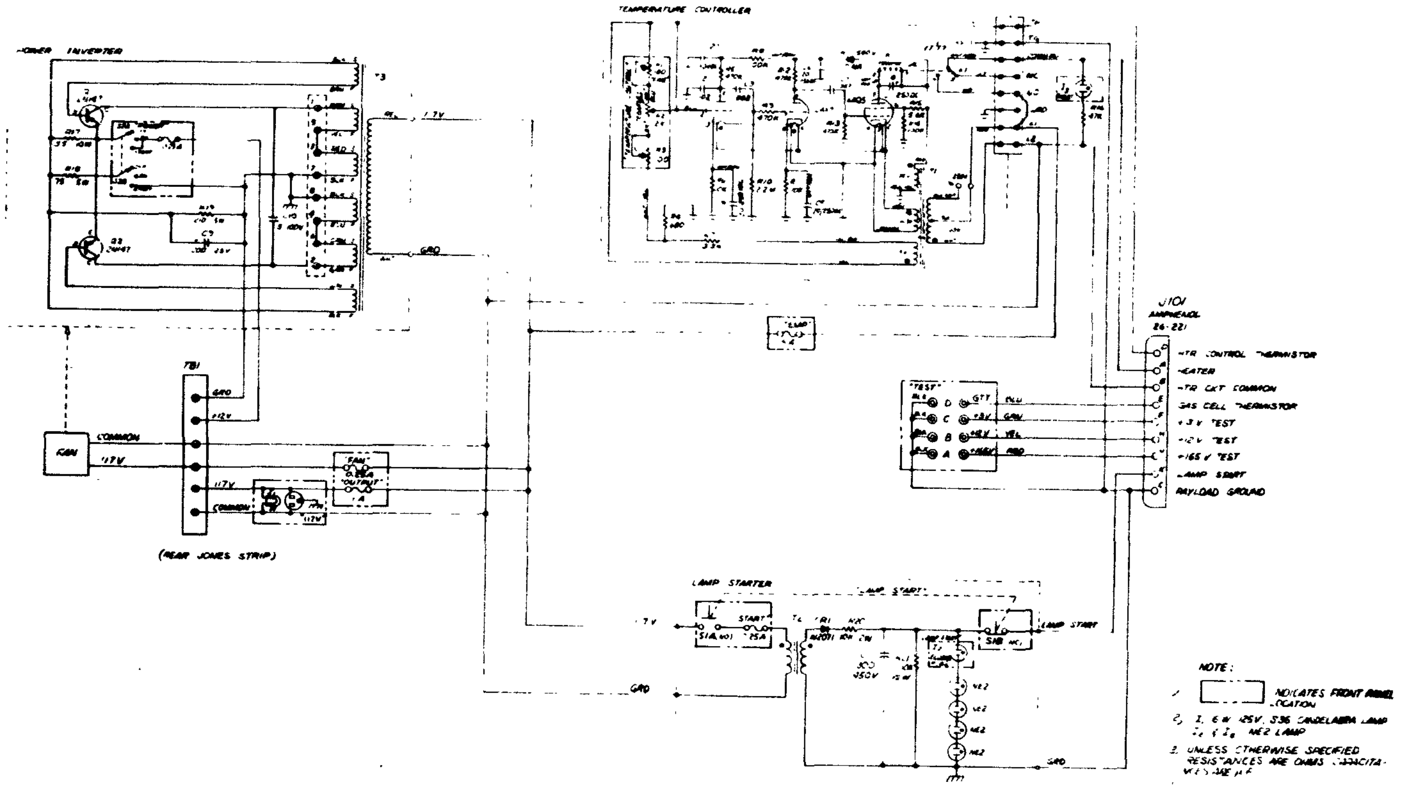


FIGURE 17
GROUND SUPPORT PANEL SCHEMATIC DIAGRAM

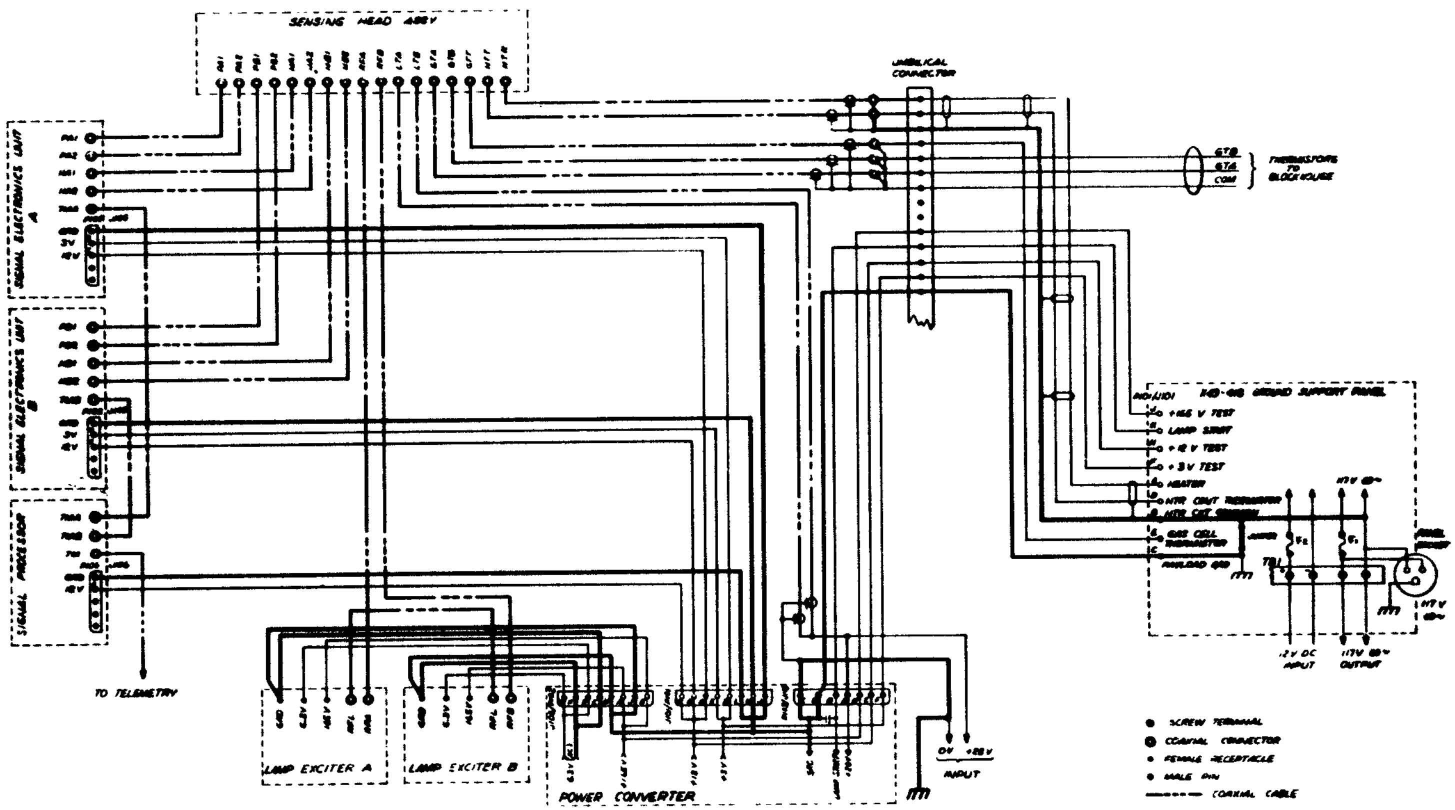


FIGURE 18
MAGNETOMETER SYSTEM INTERCONNECTION DIAGRAM

thermistors are mounted in the sensing head assembly to monitor various critical temperatures. The sensing head assembly connectors marked "LTA" and "LTB" carry +28 volts to small heaters located within the lamp assemblies: each dissipates approximately 1 watt.

VII. MAGNETIC TEST FACILITY

Two coil systems were constructed under this contract and installed and tested for the Special Weapons Center at Kirtland Air Force Base, New Mexico. The more elaborate is a four-coil set in a McKeehan arrangement, mounted with its current supply and regulator in a special aluminum trailer body. The second coil set has a conventional Hélmholtz geometry, the coils being 8 feet in diameter and coaxially spaced 4 feet apart. This system employs a minimum of metal and was designed to provide extremely fast pulses of field intensity.

A. McKEEHAN COILS

The coils in the larger of the two pair are 78.74 inches in mean diameter, while the smaller (outer) pair are each 42.56 inches in mean diameter. All four are coaxially mounted on a rigid aluminum framework, constructed so that it may be rotated independently about the vertical and horizontal axes, allowing precise placement of the system axis along the earth's magnetic field vector. The center of each of the larger coils is 14.20 inches from the coil system center; this dimension is 36.05 inches for each of the outer coils.

Each coil is wound on a phenolic form with No. 18 (AWG) stranded copper wire, insulated with polyvinylchloride. Each large inner coil consists of 60 turns; its inductance is 21.5 millihenries at 1000 c/s and its resistance is 7.2 ohms. Each of the smaller outer coils contains 32 turns, with an inductance of 3.30 millihenries and a resistance of 2.1 ohms. Connected series-aiding, as they are used in the completed system, the four coils combine to give 56.2 millihenries inductance and approximately 19 ohms resistance.

To facilitate the alignment of the system axis with the earth's magnetic field vector, a removable set of small Helmholtz coils was provided. At the installation, a rubidium vapor magnetometer was placed in the center of the McKeehan coil system, at the intersection of the system axis and that of the auxiliary Helmholtz set. The latter coils were constructed and installed to produce a field perpendicular to the axis of the McKeehan coils. Current was passed in both directions in sequence through the auxiliary set; a measurement of the total magnetic field intensity at the center was made each time, representing the vector sum of the earth's field and that produced by the auxiliary coils. The position of the McKeehan coils (and hence of the auxiliary Helmholtz pair) was adjusted until the two field intensities in a measurement were precisely equal: the McKeehan coil system axis then coincided with the earth's magnetic field vector, the framework was fixed rigidly in place, and the auxiliary coils were removed.

Removal of the auxiliary coils makes available a working volume within

the coil system measuring approximately 2 feet by 3 feet by 7 feet; the inside of the trailer is approximately 8 feet square by 20 feet long. The system produces a field intensity of 0.724 oersted per ampere. The deviation of the generated field will not exceed 0.001 per cent throughout a volume in the center of the coil system bounded by a cylinder 12 inches in diameter and 12 inches in height along the system axis. As supplied with its associated current supply and regulator, the system will produce a field intensity at the center of the system ranging from approximately +125,900 gammas (aiding) to -18,900 gammas (opposing); these figures suppose a normal field intensity at Albuquerque of 53,500 gammas. Simple power supply and metering changes (discussed below) can double this range of variation.

In the region near earth's field cancellation, effects of nearby ferromagnetic material, diurnal and even secular earth's field variations, and minor errors in coil system orientation will combine to limit the minimum useful intensity for a multiple-cell rubidium vapor magnetometer to somewhat less than 100 gammas. (It was observed, for example, that local dust contains many particles which are readily attracted to a small magnet.)

B. CURRENT SUPPLY AND REGULATOR

The Model X49-611 Current Supply and Regulator is pictured in Figure 19; its simplified schematic diagram is shown as Figure 20. The panel contains the various switches and controls for the unit and includes a temperature regulator for the electronics assemblies. The wooden box houses the latter units, which are immersed in oil and thermally insulated. The cylinder on the left in Figure 19, from which a thermometer protrudes, contains the servo amplifier. This assembly is provided with a 117-volt a-c heater to maintain the amplifier at a constant temperature above ambient. The cylinder on the right houses the current-sensing resistor and the power transistors in series with the coil system. Figure 21 shows the contents of the box partially disassembled, together with a rear view of the control panel. The chassis on the extreme left of the panel is the temperature regulator, which is identical to the type used with the magnetometer ground support panel.

Coil current is sensed as a voltage appearing across resistor R15 (Figure 20). This voltage is compared to that produced in the reference network consisting of batteries B1 and B2, and resistances R5, R6, and R8. Potentiometer R6 is connected to the large "Coil Current" dial on the panel, while R5 and R8 (located on the top of the left-hand cylinder in Figure 19) are current calibration and zero-set controls, respectively. An error current is derived from the difference between the two potentials and is amplified by transistors Q1, Q2, Q3, and Q5 and finally by the parallel combination of Q6 and Q7, which are in series with the coils L1, the sensing resistor R15, and the power supply B4. A switch-selected set of shunts can be placed across the microammeter M1, also in series with the coils, to permit measurement of coil current in several ranges.

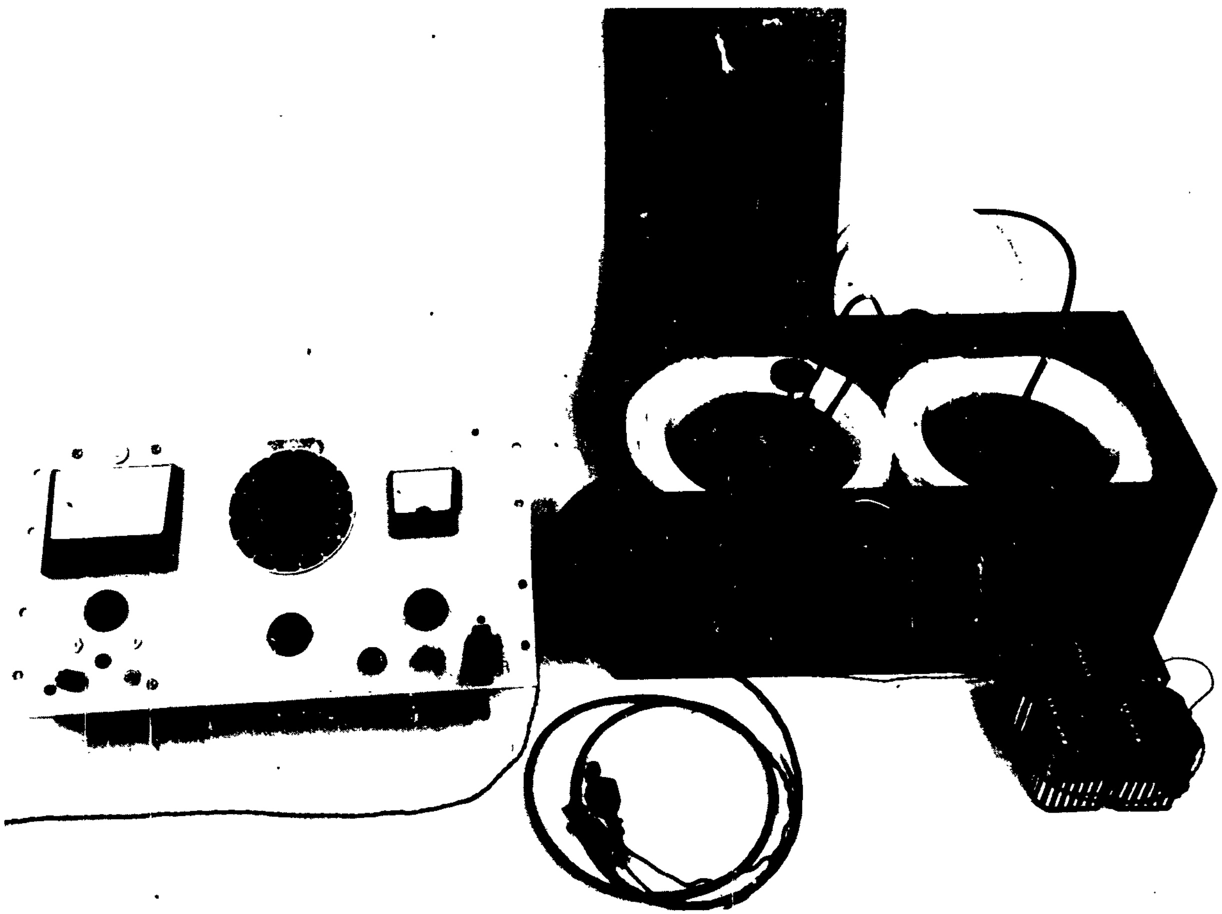
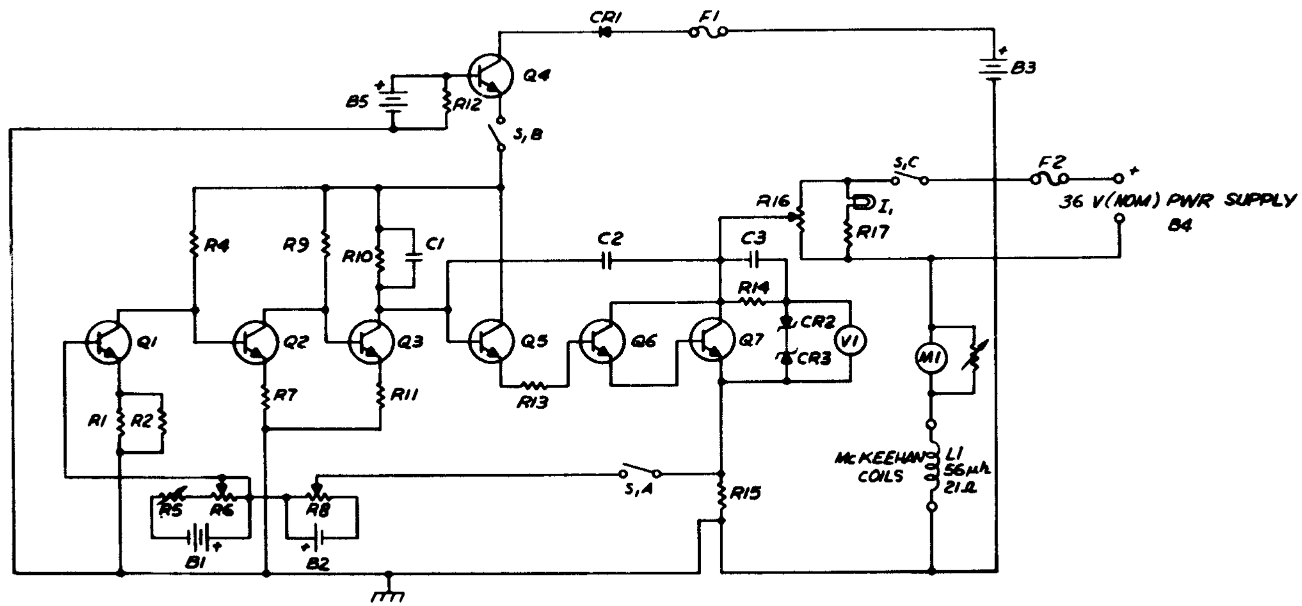


FIGURE 19
CURRENT SUPPLY AND REGULATOR



NOTES:

1. Q1, Q2, Q3, Q4 AND Q5, ALL MERCURY CELLS AND ACCOMPANYING CIRCUITRY IN 10 WT OIL OR ANHYDROUS ETHYLENE GLYCOL IN FIRST BOTTLE
2. Q6, Q7, CR2, CR3, R14, C3 AND R15 IN SECOND OIL BOTTLE
3. R1, R2, R4, R7, R9, R10, R11 & R15 ARE 1/4 WATT, 20PPM/C°, WIRE WOUND

FIGURE 20
CURRENT SUPPLY AND REGULATOR: SCHEMATIC DIAGRAM

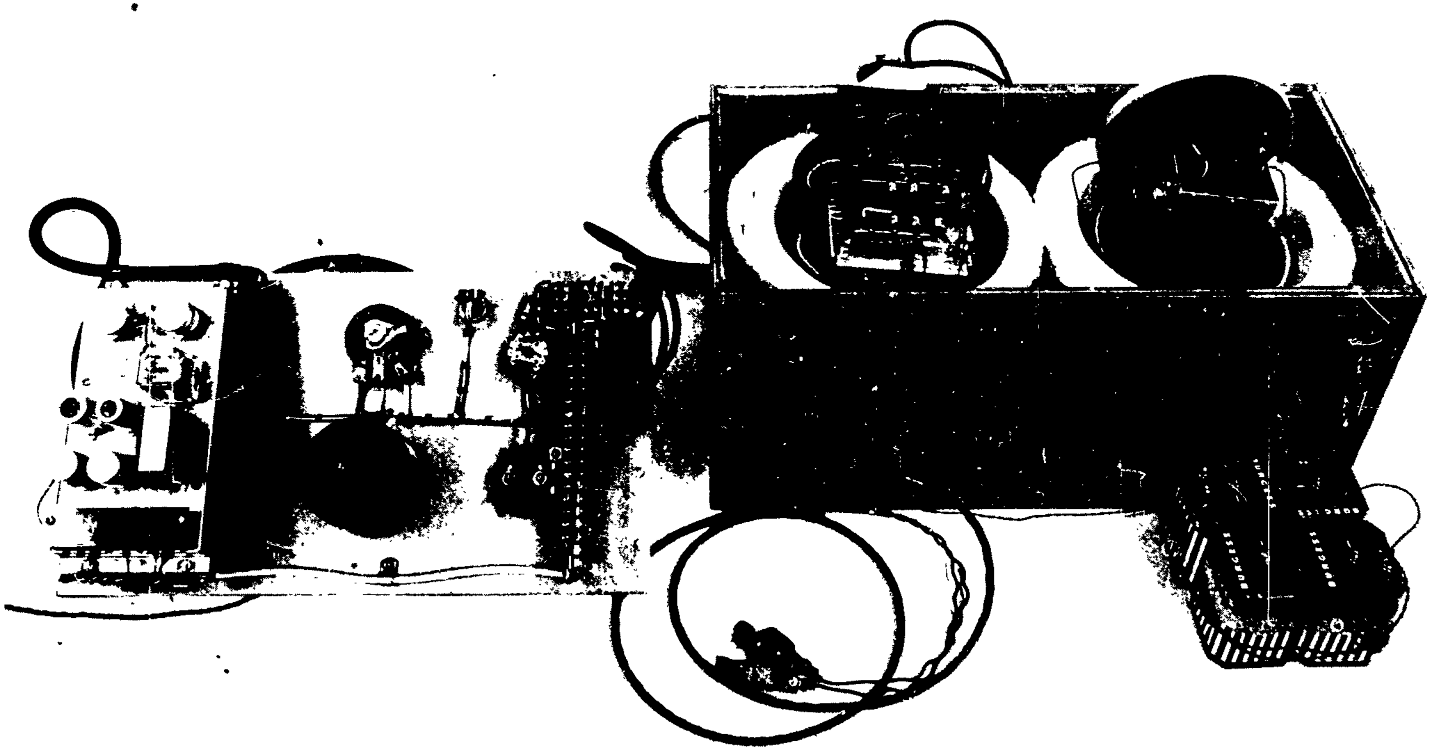


FIGURE 21
CURRENT SUPPLY AND REGULATOR: PARTIALLY DISASSEMBLED

Servo amplifier transistors Q1, Q2, Q3, and Q5 are supplied power from B3 through regulator transistor Q4, referenced to B5. The power dissipated in Q6-Q7 is set by potentiometer R16, mounted on the control panel below the coil current control. In normal operation, this dissipation is controlled by setting the collector-to-emitter voltage of Q6-Q7 to 4 volts $\pm$ 2 volts, using R16 and the voltmeter V1 on the right of the control panel. The switch immediately below this meter provides proper series resistors to allow monitoring of other important circuit voltages as well. Coil current may be reversed and turned on and off by the panel toggle switch S1, which also controls power to the servo amplifier. To protect the pass transistors Q6-Q7 from high voltages developed across the coils during any current transient, zener diodes CR2 and CR3 are placed so that one or the other will break down (depending upon transient polarity) at a voltage still safe for Q6-Q7, conducting current momentarily around these transistors. Diode CR1 prevents damage to the servo amplifier and its regulator should the polarity of B3 be inadvertently reversed. Further protection against the effects of transients, as well as increased system stability, is achieved by the high frequency degeneration provided by C1 and C2.

If the regulator dissipation control R16 and the coil current control R6 are not properly coordinated in operation, an abnormal biasing of the amplifier will be produced, resulting in the bypassing of coil current around Q6-Q7 through R14 and CR2-CR3. Although coil current will change abruptly and regulation will be lost while the system is in this condition, no component damage will be sustained. Normal operation may be regained by setting both coil current and regulator dissipation controls to their full counterclockwise positions and then resetting the desired coil current while keeping the drop across Q6-Q7 to nearly 4 volts with the regulator dissipation control.

A load change of 50 per cent will result in a current change equivalent to less than one gamma of field intensity at the coils, when an ampere is being regulated. Average initial drift of 0.5 gamma/minute will eventually stabilize at about $\pm$ 2 gammas/hour when the servo amplifier and associated components have been stabilized at 60 degrees C in their oil bath.

Higher maximum current can be regulated by increasing the primary supply voltage (B4) from 36 volts to a maximum (set by the ratings of Q6-Q7) of 60 volts; about 2 amperes can then be passed. Battery B1 should then be increased to 16 volts, and the shunts associated with meter M1 changed to accommodate the new range.

For optimum system performance at low magnetic field intensities, the current regulator and supply should be located a maximum convenient distance from the McKeehan coils to minimize field distortion due to ferromagnetic parts used in its construction. Also, direct currents should be carried through coaxial cable or carefully twisted pairs of wires to minimize current loops which could produce field distortion.

C. FIELD TRANSIENT COILS

To provide a simple means of producing transients in the earth's magnetic field on the order of an oersted over a small volume, a separate Helmholtz coil system was constructed of plywood for outdoor use. These coils were 8 feet in diameter and were coaxially spaced 4 feet apart in a frame which allowed alignment with the earth's magnetic field vector.

The two coils, connected in series-aiding, give a total inductance of 1.27 millihenries (measured at 1000 c/s). A 150-ohm resistor was placed across the coils and a 1-ohm resistor in series with the coils and the 24-volt battery allowed the current pulse to be viewed on an oscilloscope. The coils were pulsed through relay contacts, and current rise and decay times were less than a microsecond for half-oersted pulses.

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Air Force Special Weapons Center, Kirtland AFB, New Mexico.
Rpt No. AFSWC-TDR-62-101. FOUR-CELL ROCKETBORNE MAGNETOMETER. 46 p. incl illus. Final Report, January 1963.

Unclassified Report

The theory, design, installation, and successful operation of a four-gas-cell, wide-range, nearly omnidirectional rubidium-vapor magnetometer system intended for rocketborne use are described. Included is a detailed description of two coil systems and their power supplies and housing, comprising a magnetic test facility designed, fabricated, and installed at the Special Weapons Center.

Each magnetometer will operate continuously in ambient magnetic fields ranging in intensity from approximately 100 gammas to more than 1 oersted

1. Gamma radiation
2. High altitude instrument carriers
3. Magnet coils
4. Magnetic fields
5. Magnetism -- measurement
6. Magnetometers
7. Power supplies
8. Test facilities

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